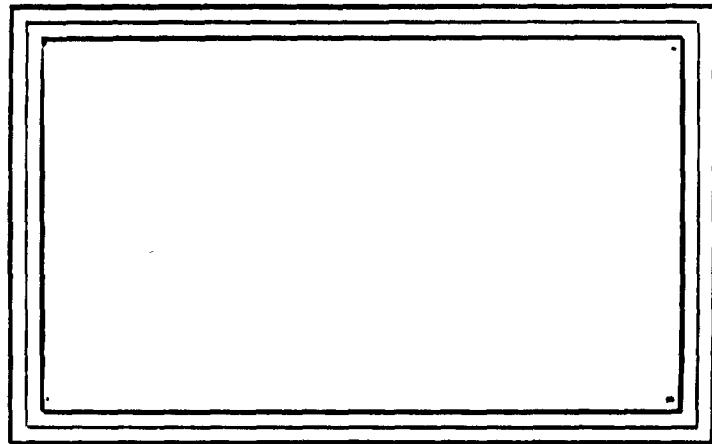


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U. S. NAVAL AMMUNITION DEPOT
Crane, Indiana

RDTRK No. 13
23 March 1960

INVESTIGATIONS INTO THE CALORIMETRIC DETERMINATION
OF THE HEAT OF COMBUSTION OF A TERTIARY PYROTECHNIC
COMPOSITION

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ABSTRACT

The calorimetric determination of the heat of combustion of a tertiary pyrotechnic composition - the thermite mixture - was studied. Results were obtained under three sets of conditions: combustion of the thermite mixture in limited air, in argon gas, and in oxygen gas at a pressure of 20 atmospheres. Procedures and results are compared each with the others, and, when possible, with theoretically predicted values.

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INTRODUCTION

An analytical procedure was needed for establishing specification limits for a thermite mixture composed of magnesium, barium peroxide, and laminac 4116 resin binder. One of the criteria proposed for inclusion in such a specification was the heat of combustion liberated -- as determined by calorimetric procedures -- upon ignition of the mixture. The details of the procedure were to be worked out by the present investigation, and experimental results compared with theoretical values calculated from accepted chemical thermodynamic properties of the system.

Three procedures for determining the heat of combustion of the thermite mixture were studied: the combustion of the mixture in a Parr Adiabatic Oxygen Bomb Calorimeter under (a) air at atmospheric pressure, (b) argon gas at a slight positive pressure after purging, and (c) sufficient oxygen gas (about 20 atmospheres) to insure complete oxidation of the mixture.

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EXPERIMENTAL PROCEDURE AND RESULTS

I. Combustion of Thermite Composition in Air and in Argon Gas

It was reasonably clear at the beginning of this study that various conditions would affect the quantity of heat liberated by the combustion, in air, of a given mass of the thermite mixture. The formulation requirements of the mixture, shown in Appendix A, indicate that the fuel components--magnesium metal, and to some extent the laminac resin--are chemically in considerable excess over the oxidizer, barium peroxide. Of the 52.4% of magnesium metal, without taking into consideration the amount of laminac resin burned, only about 6.15% of the magnesium theoretically should be consumed by the oxygen provided by the barium peroxide. How much of the remaining 46.25% of unconsumed magnesium will further react depends upon the amount of air available to it. As the amount of air varies, the amount of magnesium undergoing reaction varies, although not all of the magnesium is consumed even in the open air. Furthermore, a varying amount of the laminac resin will react with available air and with some of the oxygen provided by the barium peroxide oxidant.¹

Employing a Series 1200 Parr Adiabatic Oxygen Bomb Calorimeter, thermite samples of various sizes from 0.5 g to about 1.5 g were burned in air at a pressure of one atmosphere. The procedure used is outlined below:

1. Sampling. All of the determinations in this study were run on test samples obtained from production batches of thermite except those test samples in which for experimental reasons some component of the mixture was left out or the proportions of the components were altered; in these specific instances synthetic compositions were prepared. For purposes of standardization of testing procedures, one single production batch was used, from which two identical composite samples were drawn. Each of these samples was a composite of smaller increments drawn from representative sections of the production batch in such a way that the two composite samples should be very nearly identical. These two composite samples were used interchangeably throughout this investigation.

2. Preparation of the sample. From data in Table I it can be seen that the quantity of the test sample governs to some extent the calorific value obtained for the mixture. This is because the air in the bomb will react with a greater percent of a small sample than with a large sample, so that it is reasonable to find larger caloric values for the smaller samples. All other conditions being equal, reproducible results with a limited but constant volume of air in the bomb (capacity 328 cc.) would require the use of test samples of relatively equal weights.

¹ Excessive magnesium reacts with both oxygen and nitrogen in the air. The presence of the organic polyester-styrene resin further complicates the reaction and one of the products of the reaction is ammonia gas.

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Using a Parr Press a suitable mass of the thermite mixture is consolidated into a pellet, which should not be too hard. A stainless steel ignition cup, ignited in a muffle furnace at red heat and cooled in a desiccator, is accurately weighed. By means of forceps the sample pellet is placed in the cup, the whole weighed, and the weight of the sample obtained by difference. Since, in air or argon, it is almost impossible to ignite the thermite pellet with an electrically heated wire element, some kind of ignition aid or starter must be used to start the thermite burning. This starter will, of course, itself be ignited by the hot wire.

3. Ignition aid or starter. In the beginning of this study a stoichiometric mixture of potassium perchlorate and benzoic acid² was employed, and the values for the heat of combustion of the thermite mixture which appear in Table I were obtained under these conditions. However, it should be said that the use of the $KClO_4-C_6H_5COOH$ mixture as an ignition aid apparently involves side reactions; the experimental calorific value is markedly higher than would be predicted from theoretical considerations. It seemed desirable, then, to abandon the $KClO_4-C_6H_5COOH$ as an ignition aid for something simpler.

It seemed reasonable that a mixture of barium peroxide and magnesium, if it were much richer in oxidant than the thermite mixture itself, might ignite more easily and so serve as an ignition starter without introducing any chemical substances not already present in the original thermite mixture. This would avoid the possibility of new and indeterminate reaction mechanisms occurring, with unknown products formed in unknown quantities, about which no thermodynamic predictions could be made without extensive work. A mixture was prepared composed of 85.1% of barium peroxide and 14.9% of magnesium metal, and was found to ignite satisfactorily within the bomb by the customary technique of an electrically heated wire element. Except for some difficulty of obtaining reproducible heat of combustion values for these ignition aid pellets, due no doubt to lack of complete homogeneity of the composition from which the pellets were pressed, the BaO_2-Mg ignition aid worked satisfactorily.

4. Calorimetry procedure and reference. A pressed pellet of 85.1% BaO_2 and 14.9% Mg was then prepared and placed on the thermite pellet in the ignition cup. Care should be exercised to avoid crumbling the BaO_2-Mg pellet as it is placed in the cup. The Parr cup was placed in its holder, the 10 cm fuse wire arranged so that it pressed firmly against the ignition starter pellet for about 1 cm, and the bomb closed. Although 1 ml of distilled water is usually placed in the bomb during standardization, this water must be excluded from the bomb when burning the thermite mixture in air or argon. Water vapor formed by the intense heat of the burning mixture

² $4C_6H_5COOH + 15 KClO_4 = 15KCl + 12H_2O + 28CO_2$. Weigh ratio of benzoic acid to potassium perchlorate is 1:4.25.

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could react with the hot excess magnesium, resulting in a calorific value on the high side. If argon is used the bomb is evacuated and the argon fed into it until the pressure is positive. The bomb is then placed into the calorimeter bucket. A weighed mass of 2 kg of distilled water is added to the bucket, and then one more ml of water is added. The remainder of the calorimetry procedure followed in this study, as well as additional discussion of theory and technique, can be found in the Parr Manual No. 120, "Oxygen Bomb Calorimetry and Oxygen Bomb Combustion Methods."

5. Results. Because of difficulties encountered in attempts to burn the thermite mixture in air, further procedures were investigated: burning the mixture in an atmosphere of argon on the one hand, to remove all effects due to oxygen and nitrogen in the air combining with the hot unburned magnesium and laminac; and in an atmosphere of excess oxygen on the other hand, to oxidize all magnesium and laminac resin to their ultimate oxidation products.

Table I shows a range of from 2249 cal/g with a 0.5092 g sample to somewhere around 1700 cal/g for a 1.5 g sample. All of these test samples were ignited with $KClO_4-C_6H_5COOH$ as a starter and the heat value is more than double the value predicted from calculations of the theoretical thermodynamic value. It is very nearly impossible to arrive at a reasonable theoretical value, however, because it is not known -- at least not available in sources at hand -- precisely how much oxygen from the BaO_2 reacts with magnesium and how much reacts with laminac resin binder which coats the magnesium and BaO_2 particles. Undoubtedly these amounts can, and do, vary to some extent from sample to sample, liberating different quantities of heat. The presence of ammonia gas as one of the products may be due to the reaction of the organic resin with nitrogen in the air or, more likely, the reaction of the organic resin with magnesium nitride formed by combination of excess magnesium and nitrogen from the air present. At any rate, the exact chemical equations cannot be written so that no unqualified theoretical thermodynamic value for the heat of combustion of the reaction can be stated at this time.³

Using the $KClO_4-C_6H_5COOH$ to ignite the thermite pellet a value as high as 2249 cal/g (in air) and as low as 1405 cal/g (under argon) was obtained. Using BaO_2-Mg to ignite the thermite pellets yielded a value of 748 cal/g in argon (see Appendix E, Item 5) and values of 1399.6 cal/g and 1373.9 cal/g in air (Table II). These determinations were among the last made in this study and should be corroborated by further work.

³ The difficulty of predicting these solid state reactions is suggested by the following data: the theoretical heat of combustion of the $BaO_2 + MgO$ system is 321 cal/g, but experimental results indicate a value in the range of 383 cal/g, or 62 cal/g high. Furthermore, if we assume that all the laminac in a 1 gram sample of the thermite mixture reacts, this would account for an additional 339 cal/g, or a total theoretical value of 321 cal/g plus 339 cal/g, which equals 660 cal/g. But an experimental value of 748 cal/g was obtained under argon gas, or 38 cal/g higher than predicted.

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Although in argon gas some of the difficulties encountered by leaving air in the bomb are overcome -- for example, simplification of the reaction mechanisms -- the fundamental objections remain:

a. The thermite material is hard to ignite, so that a starter pellet or ignition aid must be used, complicating the laboratory technique, the chemical reactions, the calculations, and the ease of deriving a theoretical value against which the experimental values may be reliably compared.

b. There is a great excess of magnesium and Laminac (the fuels) over the amount of BaO₂ oxidant, so that an ashy residue of unconsumed magnesium metal, magnesium oxide, barium oxide, and unburned or thermally decomposed Laminac remain. It is suspected that one reason for poor reproducibility of results is that the BaO₂ does not always react completely with the fuel. Examination of the residue after burning in argon (indeed, sometimes in air) suggests that the pellet has not reacted to completion and that unburned pockets remain.

6. Summary. The results obtained from burning test samples of the thermite mixture in limited air supply and in the absence of air (in argon gas) serve as a rough guide as to the value of the heats of combustion under those respective conditions. It is understood that these values have not been rigorously verified and are still at the working level. For the thermite composition burning in air (about 328 cc.) values of 1399.6 cal/g and 1373.9 cal/g were found. Burning the composition under argon gas, after purging the air, resulted in a value of 748.6 cal/g. From these values at least an approximation may be made of the effect of air upon the quantity of heat liberated by the mixture.

II. Combustion of Thermite Composition in Oxygen Gas

Burning the thermite mixture under sufficient oxygen (20 atmospheres) to effect complete oxidation of all components solved many of the difficulties encountered in the use of air or argon. The thermite pellets ignited easily and reliably in oxygen without having to use a starter or ignition aid. The problem of incomplete reaction -- of unburned pockets in the thermite pellet -- was minimized. Theoretical values can be calculated for the various chemical reactions, all of which can now be written, and all of which now go to completion, and these values then compared with experimentally obtained heats of combustion. However, the heat value obtained under these conditions is actually the total potential heat available in the system, and not the heat developed under operating conditions.

⁴ Of course incomplete combustion is always a plague of calorimetry. For discussion see Section II, Parr Manual No. 120.

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1. Calorimetry procedure. After careful sampling and mixing, a mass of 0.5 to 1.0 grams of the thermite mixture is consolidated into a pellet by means of a Parr press. A stainless steel cup is prepared in the following manner: The clean cup is lined with asbestos filtered from asbestos soup on a Gooch crucible. Both the bottom and the sides must be amply protected by several applications of asbestos or equivalent to avoid melting the cup or heating it so hot that part of it may be consumed in the oxygen atmosphere.⁵ The asbestos lining is pressed into shape and dried, then finally ignited in a muffle furnace at red heat for 5 minutes, cooled in a desiccator, and weighed. Using forceps, place the thermite pellet in the cup and reweigh, obtaining the sample weight by difference. Proceed with the usual technique suitable for oxygen bomb calorimetry. Any evidence that the residue has reacted with the cup or that the cup has corroded or pitted would contribute to the suspicion that the heat value obtained is high. Incomplete combustion and reaction of the Parr cup with the oxygen atmosphere when it is overheated are probably the two major sources of error in this technique.

2. Sample calculations:

a. Thermite in oxygen

10.5532 g (lined cup and pellet sample)	Thermometer Changes
2.2570 (cup with asbestos lining)	76.45°F
0.5962 g (Weight of sample)	76.45
	76.45 Initial
	77.87
	77.38
$\Delta t \times$ Water Equivalent =	Total BTU
1.46°F \times 2459 BTU/°F =	5,901 BTU
Minus wire correction	-45.0 BTU
Corrected BTU	3545.1 BTU
	77.91°F
	-76.45
	$\Delta t = 1.46°F$

⁶ $\frac{3545.1 \text{ BTU}}{0.5962 \text{ g (weight of sample)}} = 5946.2 \text{ BTU/lb} = 3303.5 \text{ cal/g}$

⁵ Although asbestos was here used alumium cement has been suggested and would probably be superior.

⁶ The calculation methods are obtained from the Parr Manual No. 120.

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b. Polymerized Lexinac 4116 Polyester resin in oxygen

11.1428 g
10.5216 g
— .6212 g (Sample Weight)

△ t
73.53°F
73.525
76.775
76.78
76.79
76.79

△ t X W.E. = 2TU
3.265°F X 2459 = 8028.4 BTU
Wire correction -50.0 BTU
7978.4 BTU

7978.4 BTU
0.6212 g Sample = 12,843.5 BTU/#

△ t = $\frac{73.525}{3.265°F}$

12,843.5 BTU/# X 0.55556 = 7135.9 cal/g

0.55556 is the accepted value for the conversion of BTU/# to cal/gram.

3. Theoretical Calculation

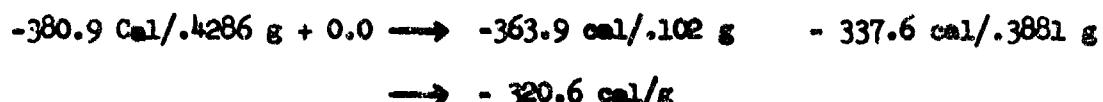
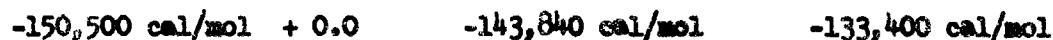
a. The wire burned in excess oxygen (20 atmospheres)

Barium peroxide - magnesium system



Barium peroxide at 42.86% is the limiting reactant; it will react with 0.0615g of magnesium to produce 0.102g of MgO and 9.3881g of BaO.

Heat of formation computations:



Exothermic

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b. Magnesium - Oxygen System



0.4625 g of Mg remain after .0615 g of total 0.5240 g were oxidized by BaO₂

$$\frac{143,840 \text{ cal/mol}}{40.32 \text{ g/mol}} = \frac{X \text{ cal}}{.767 \text{ g}} = 2736.2 \text{ cal/g}$$

c. Laminac - Oxygen System

By experiment Laminac = 7119 cal/g average

.0476 g Laminac/gram of sample

$$\frac{.0476 \text{ g}}{1 \text{ g}} = \frac{X}{7119 \text{ cal/g}} = 338.9 \text{ cal/g}$$

Total Theoretical Heat value by addition:

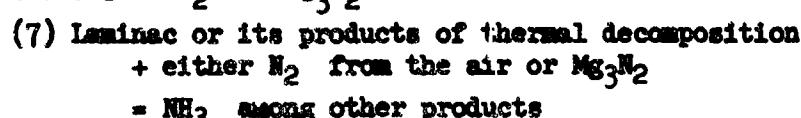
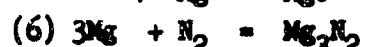
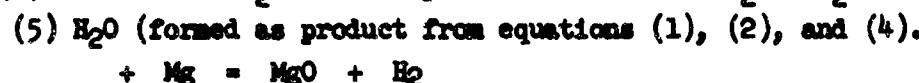
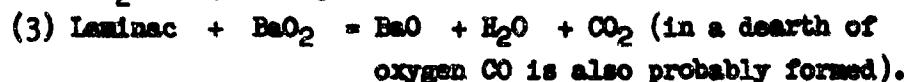
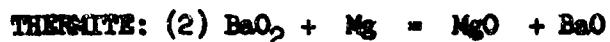
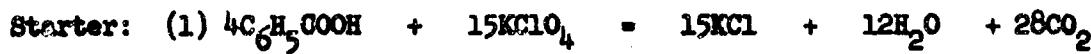
$$\begin{array}{r} 320.6 \text{ cal/g} \\ 2736.2 \text{ cal/g} \\ \hline 338.9 \text{ cal/g} \\ \hline 3395.7 \text{ cal/g} \end{array}$$

3395.7 cal/g theoretical heat value compares reasonably with the experimental value obtained of 3320.4 cal/g. See Appendix B, Item 1. No satisfactory theoretical heat value is available for the thermite in air or argon because the reaction systems and their weights cannot be written.

CONCLUSIONS AND RECOMMENDATIONS

It was found in this study that the thermite samples burning in air, and using a KClO₄-C₆H₅COOH pellet to initiate the reaction, yielded a higher heat of combustion than could be explained by theoretical calculations. After applying corrections for the heat evolved by the KClO₄-C₆H₅COOH reaction, the fuze wire consumed, and the reaction of magnesium and Laminac resin with oxygen and nitrogen of the air, the experimental heat of combustion values were still considerably higher than the theoretical values. To derive these theoretical values, the sum of all reactions in the system must be known, as well as the weights of products and reactants involved. To write the chemical equations for all of the reactions may be possible, but to discover the weights involved would be a very tedious matter. Although there may be others, the following are reactions that were assumed to occur:

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No satisfactory theoretical solution seems feasible under these conditions.

Secondly, it was found that burning in air, and using the $KClO_4-C_6H_5COOH$ starter, did not allow for any high degree of reproducibility. Deviations from the average value for the heat of combustion include 3.5%, 0.93%, 2.5%, 4.7%, and 1.6%. Lack of uniformity in the composition of the specimen samples themselves, as well as differences in the amount of BaO_2 reacting with magnesium on the one hand and with Laminac on the other hand, no doubt account for some of this variation.

It is not recommended that $KClO_4-C_6H_5COOH$ mixtures be used to start the combustion of the thermite pellet.

Two values were obtained in which thermite samples were ignited by a BaO_2-Mg starter pellet. Reproducibility of results were satisfactory in these two instances, in which the test specimens averaged 1386.8 cal/g and deviated from the average by 0.94%. While an insufficient number of specimens were run, the values here indicate the heat of combustion range one would expect for the thermite mixture in limited air.

If it is desirable to find the actual heat of combustion of the isolated mixture, it must be burned under argon gas; the ignition starter, again, should be a mixture of BaO_2-Mg such as the one used in this study. Whatever the proportions of BaO_2-Mg employed, great care must be used to insure that the mixture is homogeneous. We therefore recommended that three or four pellets be pressed out of the BaO_2-Mg mix to be used as the starter, and the average heat of combustion determined by calorimetry be used in correcting for heat put into the system by the starter pellet. These three or four pellets probably should not vary one from the other by more than 40 cal/g.

Most of the work in this study was done on burning the thermite composition in an excess of oxygen, because here we can take all the fuels to

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complete oxidation, we can predict the chemical reactions, and we can compute a reasonable theoretical value for the heat of combustion. A theoretical heat of combustion of 3395.7 cal/g was derived and this compares favorably with experimental values listed in Table III: for example, 3303.5 cal/g, 3266.4 cal/g, or 3477.6 cal/g. With one exception all of the values fell within \pm 100 cal/g. At this time in the investigation it would seem reasonable to expect values for the heat of combustion of the thermite mixture to fall within \pm 100 cal/g of the theoretical heat of combustion of 3395.7 cal/g, and furthermore to expect the great majority of the values to fall within 100 cal/g below the theoretical heat of combustion.

The major sources of error, which would show as poor reproducibility of results in a series of determinations performed on test specimens taken from the same sample, include: (a) oxidation of the Parr cup, (b) incomplete combustion, (c) lack of uniformity in composition of the test specimens taken from the same sample, and (d) slow flow of heat from the porous combustion products in the cup, which have a low thermal conductivity, to the calorimetric fluid, so that the operator may be led to make premature final thermometer readings.

TABLE I

Data developed on burning thermite ignition mixture in an air volume of 328 c.c. using $\text{KClO}_4\text{-C}_6\text{H}_5\text{COOH}$ ignition aid

<u>Sample Wt.</u>	<u>Igniter Wt.</u>	<u>Δt in°F</u>	<u>Total BTU</u>	<u>Correction in BTU</u>	<u>Heat of Combustion in cal/g</u>
0.5099 g	0.4181 g	76.935-75.72=1.215°F	2987.7	-923.3	2249.2
0.7031 g	0.5796 g	78.30-76.65=1.65°F	4057.4	-1285.6	2190.2
1.0265 g	0.4865 g	78.67-76.79=1.88°F	4622.9	-961.8	1981.5
1.1503 g	0.7943	79.91-77.50=2.41°F	5926.2	-1752.7	2015.7
1.4278	0.3836	78.75-76.65=2.1°F	5163.9	-844	1680.9
1.5796	0.6744	81.32-78.6=2.72°F	6688.5	-1498.4	1825.4

TABLE II

Data developed on burning thermite ignition mixture in air volume of 328 c.c. using 85.1% BaO_2 - 14.9% Mg ignition aid

1.1141 g	1.7613 g	77.35-75.21=2.14°F	5262.3	-2455.5	1399.6
1.1883 g	0.5411 g	73.71-72.20=1.51°F	3713.1	-774.4	1373.9

TABLE III

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Data developed on burning thermite mixture in 20 ATM of oxygen.

Sample Wt.	Cup Lining	Δt in °F	Total BTU	Correction in BTU	Heat of Combustion in cal/g
0.3935 g	None	76.775-75.75=1.025°	2520.5	-41.0	3500.6 (1)
0.3095 g	None	77.05-76.275=0.775°	1905.7	-33	3456.6 (2)
0.6647 g	Alundum Pvd.	78.82-77.25=1.57°	3860.6	-36	3196.6 (3)
0.4550 g	Asbestos	79.05-77.90=1.15°	2655.7	-32	3203.6
0.4584 g	Asbestos	79.75-78.61=1.14°	2803.3	-38	3351.4
0.8539 g	Asbestos	78.39-76.33=2.06°	5065.5	-45	3266.4
0.5962 g	Asbestos	77.91-76.45=1.46°	3390.1	-45	3393.5
0.4677 g	Asbestos	78.27-76.90=1.37°	3368.8	-34	3961 (4)
0.5259	Porcelain Crucible	79.65-78.43=1.22°	2999.98	-38	3129 (5)
0.7416 g	Asbestos	73.25-71.35=1.90°	4672.1	-30	3477.6
Average of accepted results					3320.4 cal/g

NOTES:

1. Rejected: stainless steel cup melted by heat of reaction. Some of the cup probably burned.
2. Rejected: same reasons as above.
3. Rejected: Appearance of incomplete combustion.
4. Rejected: side of cup attacked and partly consumed.
5. Rejected: Crucible broken by heat. Suspect incomplete combustion.

Alundum cement would probably endure the heat better than asbestos. Furthermore, it has been suggested that asbestos may, in fusing, undergo molecular rearrangements which absorb heat.

TABLE IV

Data developed on burning Laminac-Lupersol (polymerized, solid) in 20 ATM of oxygen

Sample Wt.	Δt in °F	Total BTU	Correction in BTU	Heat of Combustion in cal/g
0.6212	76.79-73.525=3.265°	8028.4	-50.0	7135.9
0.5084	75.580-72.903=2.677°	6582.7	-42	7147.2
0.4576	77.98-75.59=2.39°	5877.0	-50	7074.5
Average				7120 cal/g

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APPENDIX A

I. Chemical composition of Thermite Ignition Mixture

<u>Component</u>	<u>Parts by Weight in Production Batch</u>	<u>Percent</u>
Barium Peroxide	450	42.86%
Jet Magnesium	150	14.30
RDA 89 Magnesium	400	38.09
Laminac 4116	49.25	4.68
Lupersol	0.75	0.07
	<u>1050.00 parts</u>	<u>100.00%</u>

II. Percent of Reactants in Thermite Ignition Mixture

<u>Component</u>	<u>Percent</u>
Barium Peroxide	42.8%
Magnesium	52.4
Laminac-Lupersol	4.8
	<u>100.0%</u>

III. Specification Requirements for Ingredients used in Thermite Ignition Mixture

<u>Component</u>	<u>Specification</u>
Barium Peroxide	JAN B 153 Class A
Jet Magnesium	Type 3 Gran 16
RDA 89 Magnesium	Type 3 Gran 17
Laminac 4116 Polyester Resin	MIL-STD-708
Lupersol	

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APPENDIX B

Miscellaneous Heats of Combustion Developed in this Study

1. Thermite mixture without laminac binder, burned under 20 atmospheres of oxygen: A comparison among the values obtained by burning a synthetic mixture without the laminac binder, a production sample with laminac from which the experimentally determined heat of combustion of laminac is subtracted, and the theoretical heat of combustion of the thermite mixture burned in oxygen, from which the experimental heat of combustion of laminac is subtracted:

<u>Synthetic Thermite Samples; without laminac, burned under oxygen</u>	<u>Production Thermite Samples; without laminac, in O₂; value for laminac subtracted</u>	<u>Theoretical Heat of Combustion of Thermite in oxygen; value for laminac subtracted</u>
3142.8 cal/g	3320.4 cal/g	3395.7 cal/g
3063.8 cal/g	<u>-339.0 cal/g</u> laminac	<u>-339.0 cal/g</u> laminac
2986.1 cal/g	2981.4 cal/g	3056.7 cal/g
3064.2 cal/g		
Deviation from Theoretical +0.25%	-2.5%	0.0%

<u>Sample Wt.</u>	<u>Ignition Wt.</u>	<u>Δ t in °F</u>	<u>Total BTU</u>	<u>Correction in BTU</u>	<u>Heat of Combustion in cal/g</u>
2. 0.8752 g	0.6979 g	1.525°	3749.97	-1536.47	1405.1
3. 1.4669 g	0.3313 g	1.47°	3614.7	- 742.6	1087.7
4. 1.5204 g		0.86°	2114.7	- 29	762.0
5. (a) 1.2887 g		1.185°	2913.9	- 27	1244.6
(b) 1.1028 g		0.93°	2286.8	- 22	1140.9
6. 0.8807 g	0.3478 g	0.65°	1598.35	- 15	748.8

Conditions under which above heats of formation were determined:

2. Thermite in oxygen, with $\text{KClO}_4\text{-C}_6\text{H}_5\text{COOH}$ ignition aid.
3. Thermite in argon, without laminac binder, using $\text{KClO}_4\text{-C}_6\text{H}_5\text{COOH}$ ignition aid.
4. Synthetic sample of 85.1% FeO_2 - 14.9% Mg, in argon.
5. $\text{KClO}_4\text{-C}_6\text{H}_5\text{COOH}$ mixture [4.25:1] in argon.
6. Thermite in argon using $\text{FeO}_2\text{-Mg}$ ignition aid.